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INTEGRATED GEOPHYSICAL AND GEOLOGICAL STUDY OF EARTHQUAKES IN NORMALLY ASEISMIC AREAS

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The integration of information from seismology, precise leveling, sea level variations, geomorphology, photogeology, the sedimentary record, igneous activity, and faulting is resulting in the formulation of a better dynamic framework for understanding earthquakes in normally aseismic regions in order to provide better criteria for descrimination of such events. Analysis of geodetic leveling and sea level data has revealed a complex system of vertical crustal movements that can be correlated with the structure

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20. and seismicity of the eastern United States. Uplift of the Appalachians relative to the coast is presently occurring at rates 2-3 orders of magnitude larger than the Post-Jurassic average. Correlation of vertical movements with topography indicates that the factors responsible for creating topographic relief are presently active at an accelerated rate. A study of Cenozoic faulting in the eastern United States indicates that tectonic activity in this region cannot be accounted for by a simple stress pattern. Some of these faults appear to be reactivated Paleozioc faults while others may have moved only during the Cenozoic era. New seismicity maps for the eastern United States and China are being used to examine spatial and temporal patterns in the seismicity of these normally aseismic regions. Research into the seismicity and tectonics of China has produced a bibliography of material related to this little known region.

TECHNICAL REPORT SUMMARY

Technical Problem

The basic problem to which this study is addressed is to understand why and how earthquakes occur in normally aseismic regions so as to improve capability for identification of these events. We understand in some depth why earthquakes occur in active tectonic regions, i.e., near the boundaries of the lithospheric plates of plate tectonic theory. However, our understanding of earthquakes far away from these boundaries (intraplate earthquakes) is very limited and consists mainly of speculation.

These intraplate earthquakes are important for a number of reasons. Although they do occur less frequently than in active tectonic regions, they sometimes reach large magnitudes. Also, the propagation of seismic energy is more efficient in at least some intraplate regions. These facts are important in determining seismic hazard ratings for intraplate areas as well as in distinguishing between these earthquakes and nuclear explosions.

General Method

Since intraplate earthquakes occur infrequently, seismic data on them are limited and data from other sources besides seismology must be brought to bear on the problem. We are continuing to gather and synthesize evidence from precise leveling, theoretical geophysics, sea level changes, geomorphology, photogeology, the sedimentary record, igneous activity, and faulting. Thorough literature reviews of several of these areas have been conducted and are being continued in those areas for which they are incomplete. Enormous volumes of data have been obtained from, and with the cooperation of, the National Geodetic Survey. This data is presently being reduced and analysed at Cornell. The first complete map of vertical crustal movements in the eastern United States is presently being prepared jointly by Cornell and the National Geodetic Survey. Original theoretical investigations are being initiated in order to relate empirical results with physically describable mechanisms for generating earthquake-producing stresses. The program in photogeology is active in obtaining and analysing ERTS and SKYLAB photographs of Eurasia and the United States, as well as scheduling special U-2 missions to obtain needed coverage in the eastern United States. Completed mosaics constructed from ERTS band 7 images of the Mississippi embayment of the United States, and the Tarim Basin, Tibetan platform and Central Area of China are being correlated with geostructure. Ground control in China is limited to Chinese publications and the results of the Sino-Swedish Expeditions. Integration of mapping of photo features with fault plane solutions and statistics of earthquakes, as well as in situ stress measurements, is being carried out to obtain a better picture of intraplate stress systems. Field work is being undertaken to verify and identify features discriminated in the photos of the eastern United States, as well as to investigate areas of particular interest as indicated by leveling and seismic studies.

Particular attention is being directed toward the very seismically active areas in China. Ongoing literature searches and translations of heretofore little used references on Chinese geology, seismicity, and tectonics are providing a unique data bank for study of the area of

China. A working relationship is being developed with U.S. Geological Survey geologists specializing in China, as well as with the Geophysical and Geological Institute of China. One graduate student is preparing to engage in field research in Taiwan with partial support by NSF. Although Taiwan is not strictly an intraplate region, this study should be very valuable in obtaining more information about mainland China.

Although most of the effort in this study has been applied to the eastern United States, where field checking is possible and data is more readily available, efforts are continuing to integrate and expand on data dealing with both eastern and western Europe, as well as less studied foreign regions.

Technical Results

The main results obtained during the period covered by this report come from studies of precise leveling, faulting, seismicity and literature compilations. Each of these topics is covered in more detail in other sections of the technical report.

The analysis of precise leveling data basically entails determining the change in elevation of a reference point (bench mark) by comparing elevation determinations of that point by surveys carried out several years apart (typically 25 years). The difference between the two determinations divided by the time interval between levelings yields the apparent average relative velocity of that point for that time interval. It has been found that the eastern United States is undergoing vertical crustal movements with higher rates than implied by the sedimentary record. Moreover, it appears that these movements can be correlated with both geologic structure <u>and</u> seismicity, thus becoming the first directly measured parameter to be associated with seismicity in the eastern United States, a normally aseismic region.

A compilation of known occurrences of post-Cretaceous faulting in eastern North America has been compiled in order to provide a record of recent tectonic activity in this region. The fault movements have been dated as younger than offset Cretaceous, Tertiary, or Quaternary sediments, Cretaceous kimberlites, or Pleistocene glacial striations. Both reverse and normal faults of this type have been documented. Some of these faults indicate reactivation of pre-existing weaknesses. The stresses inferred from these faults are not consistent with a dominant horizontal compression in the North American plate.

In order to facilitate research on problems of Chinese tectonics and seismicity, a bibliography of papers related to the geology, seismicity, tectonics and recent crustal movements of China has been prepared from various international journals. Two very useful maps of the seismicity of eastern North America have been compiled. One shows all known historic and instrumental seismicity from 1534 to present while the other is limited to earthquakes that have happened between 1928 and the present time. These maps have been used to delineate and identify prominent trends in eastern North American seismicity.

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Post-Cretaceous Faulting in eastern North America

Exposed post-Cretaceous faults in eastern North America provide evidence of tectonic activity during prehistoric time. This activity may have been similar to minor-to-moderate historic seismic activity. Fault movements are dated as younger than offset Cretaceous, Tertiary, or Quaternary sediments, Cretaceous kimberlites, or Pleistocene glacial striations. Both reverse and normal faults occur. They are found in the central Mississippi River and the southeast United States, both areas of moderate historic seismicity. They also occur in the glaciated northeast United States and eastern Canada, but not always in areas of historic seismicity. In all of the above regions at least some of the faults occur along pre-existing weaknesses. Surface faulting probably occurred on most of the faults.

The reverse faults in the unglaciated areas are the faults most clearly associated with earthquakes. The amounts of near-surface displacement on these reverse faults imply that some faults have moved several times and that moderate-to large-magnitude earthquakes could have occurred on some of them. The reverse faults in glaciated areas have small displacements and may be related to compression caused by glacial unloading. The faults which offset kimberlites could be associated with stresses active only during intrusion.

Table 1 and Figure 1 summarize the known occurrences of post-Cretaceous faulting in the eastern United States. Their recognition depends on an number of factors besides tectonics. The distribution of Cretaceous and younger sediments suggests that less than one in ten faults would offset such sediments. Possibly one in a thousand post-Cretaceous faults would be exposed somewhere along its length. Perhaps one in ten exposed faults datable as post-Cretaceous have been seen and reported by geologists. The faults in Table 1 represent the displacement equivalent of about 100 magnitude 6 earthquakes over a period of approximately 100 million years. These approximations then imply the occurrence of a magnitude 6 earthquake once every ten years, which is in rough agreement with historical seismicity.

If the reverse faults in the unglaciated areas were caused by tectonic stresses which are still active at present, then these data suggest that moderate- to large-magnitude earthquakes and surface faulting might occur at localities which have had only minor earthquakes historically. These faults suggest that no simple dominant stress pattern is responsible for seismicity in eastern North America. This result contradicts the hypothesis of Sbar and Sykes (1973) that the eastern portion of the North American plate is dominated by an east-west compression.

TABLE 1. DESCRIPTIONS OF FAULTS

Location	Type of faults[*]	Strike	Dip	Displacement (meters)	Youngest faulted rocks	Observed 1976	Literature reference
Benton, Kentucky	V	N45E	90	0.3	Pliocene(?) terrace gravels	-	Rhoades and Mistler(1941)
Benton, Missouri	S	-	-	>15	Cretaceous sediments[‡]	-	Grohskopf (1955)
Bloomfield, Missouri	-	N55W to N30W to NS	-	3-8	Tertiary sediments	-	Grohskopf (1955)
Bloomfield, Missouri	-	N50W to NS to N30E	-	3-6	Tertiary sediments	-	Grohskopf (1955)
Buckhorn Crossroads, North Carolina[†]	S	N51E	48 NW	0.3	Cretaceous sediments[‡]	-	White(1952)
Burlington, Vermont	-	-	-	0.9	Cretaceous kimberlite[‡]	-	Thompson (1853, p. 53)
Clifton Forge, Virginia[†]	V	N25W	90 (E side down)	5-6	Tertiary gravels[‡]	X	White(1952)
Commerce, Missouri	-	-	-	-	Pliocene(?) gravels	-	Grohskopf (1955)
Crystal River, Florida[†]	-	N45W	-	-	Eocene limestone	-	Vernon(1951)
Deep River, North Carolina	N	-	-	>0.5	Pliocene(?) sediments	-	Reinemund (1955)
Drewrys Bluff, Virginia[†]	S	-	>50	<0.5	Cretaceous sediments	-	Cederstrom (1945)
Drewrys Bluff, Virginia	S	N45E	45 S	0.8	Cretaceous sediments	S	
Grand Rivers, Kentucky	V	N18E	90 (E side down)	-	Cretaceous sediments	-	Rhoades and Mistler(1941)
Greenwood, Virginia[†]	S	N20E	57 E	1.5	Pleistocene terrace gravels[‡]	S	Nelson(1962)
Hillsboro, Virginia	-	-	>45	0.9	Tertiary gravels	-	White(1952)
Hydro, North Carolina[†]	S	N40E	50 NW	5	Tertiary gravels[‡]	X	White(1952)
Idalia, Missouri	-	S45W	-(NE side down)	20	Tertiary sediments	-	Farrar and McManamy(1937)
Idalia, Missouri	-	S55E	-	>15	Pliocene(?) gravels	-	Grohskopf (1955)
Kentucky Dam, Kentucky	V	N60E	90	>30	Cretaceous sediments	-	Rhoades and Mistler(1941)
Ludlowville, New York	S	-	-	0.8	Cretaceous kimberlite[‡]	-	Matson(1905)
Pumpkin Hollow, New York[†][#]	S	N40E	85 SE	.05	Pleistocene glacial striations[‡]	S	Oliver and others(1970)
Quantico, Virginia[†]	S	N75W	50 S	0.25	Cretaceous sediments	X	Cederstrom (1945)
Saluda, North Carolina	S	N80E	11 S	>0.5	Quaternary(?) terrace gravels[‡]	-	Conley and Drummond (1965)
Saluda, North Carolina	S	N8E	87 S	>5	Quaternary(?) colluvium[‡]	-	Conley and Drummond (1965)
Saluda, North Carolina	R	N40W	20 NE	>6	Quaternary(?) colluvium[‡]	X	
Taughannock Falls, New York	N	-	-	0.5	Cretaceous kimberlite[‡]	-	Matson(1905)
Upper Marlboro, Maryland	R	-	-	>0.3	Pleistocene sediments	-	Dryden(1932)
Valcour Island, New York	-	NS	-	-	Cretaceous kimberlite[‡]		Hudson and Cushing(1931)
Valcour Island, New York	-	N50E	-	-	Cretaceous kimberlite[‡]	-	Hudson and Cushing(1931)
Washington, D.C.	-	-	-(E side down)	>2	Cretaceous sediments[‡]	-	Carr(1950)
Washington, D.C.[†]	R	-	>60	~1	Pleistocene terrace gravels[‡]	-	Darton(1939)
Washington, D.C.	R	S5W	80 W	>2	Cretaceous sediments[‡]	X	Carr(1950)

[*] R (reverse), N (normal), V (vertical), H (horizontal)
[†] Photograph of fault is published in the literature reference.
[‡] Paleozoic or Precambrian bedrock is also exposed and offset by the fault.
[#] This locality is representative of many postglacial faults listed in the literature reference.

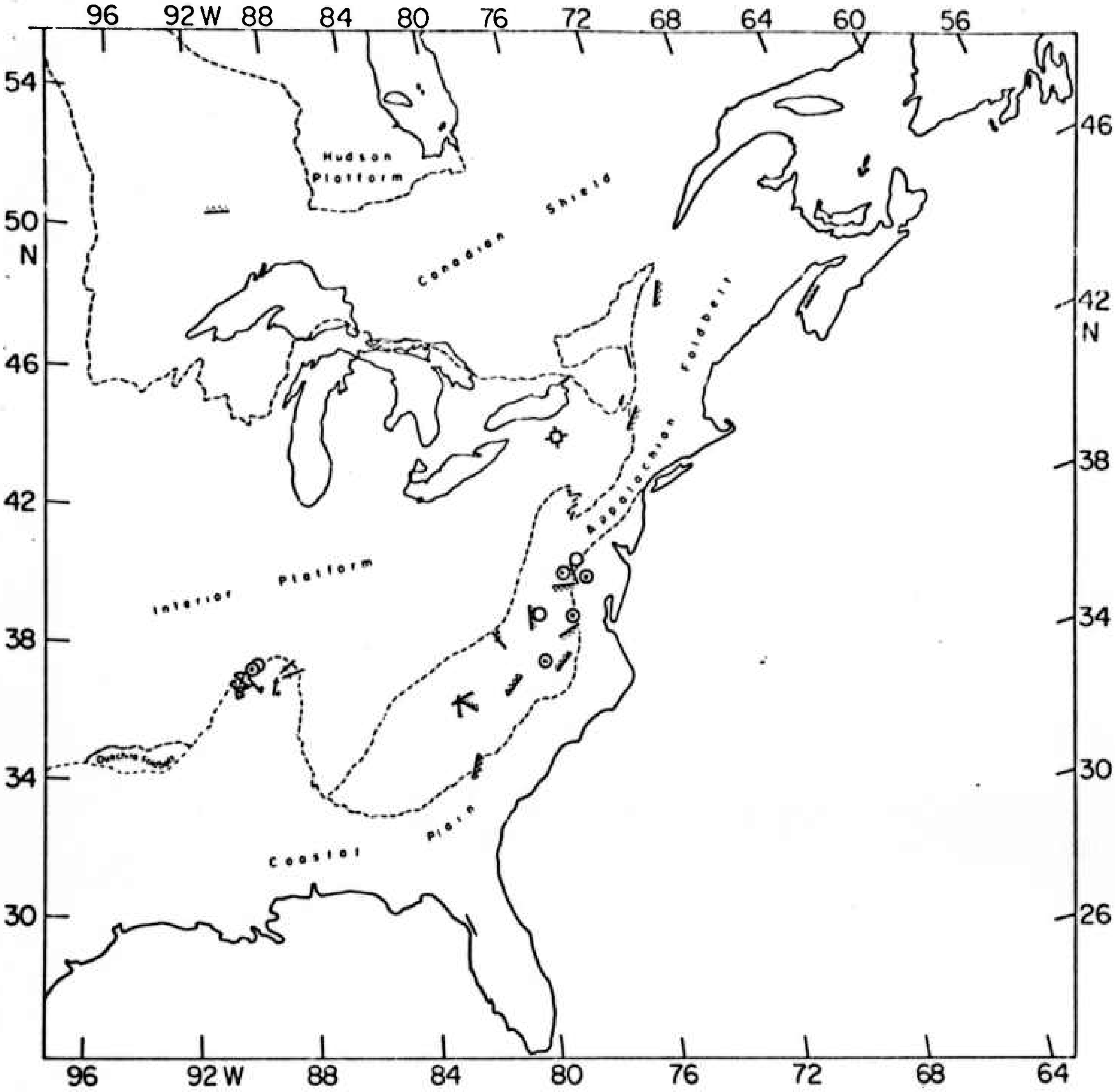


Figure 1. Post-Cretaceous faults in eastern North America. Data from Table 1 and three more representative postglacial fault locations (Ontario, Quebec, and Nova Scotia) from Oliver et al, 1970. Line segments show strikes of faults, short cross segment indicates a vertical fault, D on downthrown side; circles show faults with unreported strikes; R indicates reverse fault; N indicates normal fault; pointed barbs indicate reverse faults; straight hatchures indicate normal faults; barbs and hatchures are on the downdip side of fault; hourglass symbols show fault zones where fault strikes vary within limits shown; small square between four short line segments indicates a horizontal fault.

Implications for Further Research

Studies thus far indicate that no single stress field can be invoked to explain intra-plate seismicity. The studies of post-Cenozoic faulting suggest that reactivation of previous tectonic features may explain some but not all seismic events in the eastern United States. Although several prominent seismic trends can be identified in intra-plate areas, a coherent and comprehensive explanation of their occurence is still lacking. Results of leveling studies to date indicate that this method may reveal enough of the dynamic mechanism at work presently to allow solid inferences about the nature of the stresses acting to produce earthquakes in normally aseismic areas. Continued analysis of leveling data, integration of geophysical and geological parameters in all aseismic areas, and expanded theoretical work on possible mechanisms should provide even more clues as to the nature of intra-plate seismicity. Such an understanding is a vital first step toward discrimination of seismic from nuclear events.

Seismicity of Eastern North America

Over a thousand earthquakes have occurred in eastern North America during the past few hundred years. However, destructive earthquakes in this intraplate region are not numerous compared with shocks along active plate margins. Earthquakes with intensity X and above have occurred in several heavily populated areas. Examples of these destructive and large intraplate earthquakes include: Charleston, South Carolina, 1886; New Madrid, Missouri, 1811-1812; Cape Ann, Massachusetts, 1755; St. Lawrence River Region, 1633. Compared with shocks of similar magnitudes and energies along the plate boundaries, these events are equally hazardous. Thus, although they do not occur frequently, large intraplate shocks are an environmental risk and must be taken into account in the design and location of large, man-made facilities such as nuclear power plants, dams, and other large structures.

In order to examine certain characteristics of the spatial relationships and the intensities of reported earthquakes, two seismicity maps of Northeastern America were made. Map 1 contains all known historic and instumental seismicity from 1534 to present. Map 2 includes all earthquakes that occurred between 1928 and the present. Earthquakes of the Panama Zone, Puerto Rico and the Virgin Islands are not included on these maps because they lie outside the normally aseismic zone.

Sources of information used in developing these maps are W. E. T. Smith's 1534-1959 map and 1928-1959 map from Earthquakes of Eastern Canada and Adjacent Areas, Dominion Observatory Reports, Seismicity of the Southeastern United States by G. A. Bollinger, Earthquakes of the Stable Interior with Emphasis on the Midcontinent, by J. Docekal, U. S. Earthquakes Reports from NOAA, and United States Earthquakes by the United States Department of Commerce.

The tectonic map of North America with scale of 1:5,000 is adopted as the Base Map, with the intention of overlay comparison with tectonic regime. Four group intensities are used: I-IV; V-VI; VII-IX; and X-XII. For multiple earthquakes at any specific location only the largest intensity recorded during that period is plotted. Minor aftershocks of large earthquakes are not shown on these maps.

Based on spatial patterns reflected in these maps, earthquake activity is interpreted as occurring in the following seismic zones:

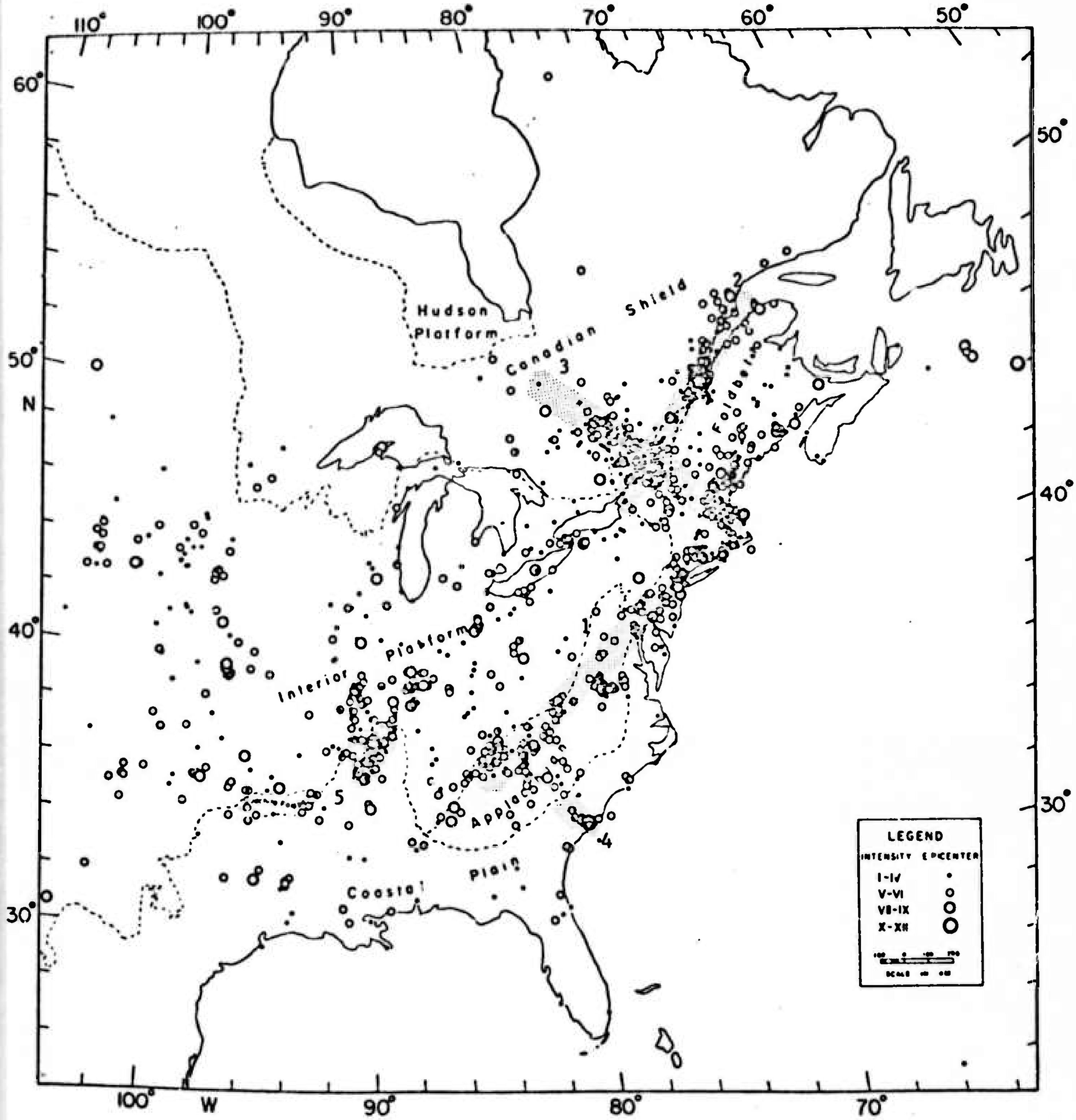
1) The Appalachian seismic zone, which extends from Maryland to central Alabama in the Valley and Ridge and Blue Ridge Provinces.

2) The St. Lawrence seismic zone, which extends along the St. Lawrence Seaway from northern New York to the mouth of the St. Lawrence River.

3) The Boston-Montreal seismic zone, which extends from Boston to northern Quebec, transverse to regional structures.

4) The South Carolina-Georgia seismic zone, which spans across the Piedmont and Coastal Plain provinces, cutting across regional structures.

5) The New Madrid seismic zone, which trends along the Mississippi River in the Mississippi embayment.



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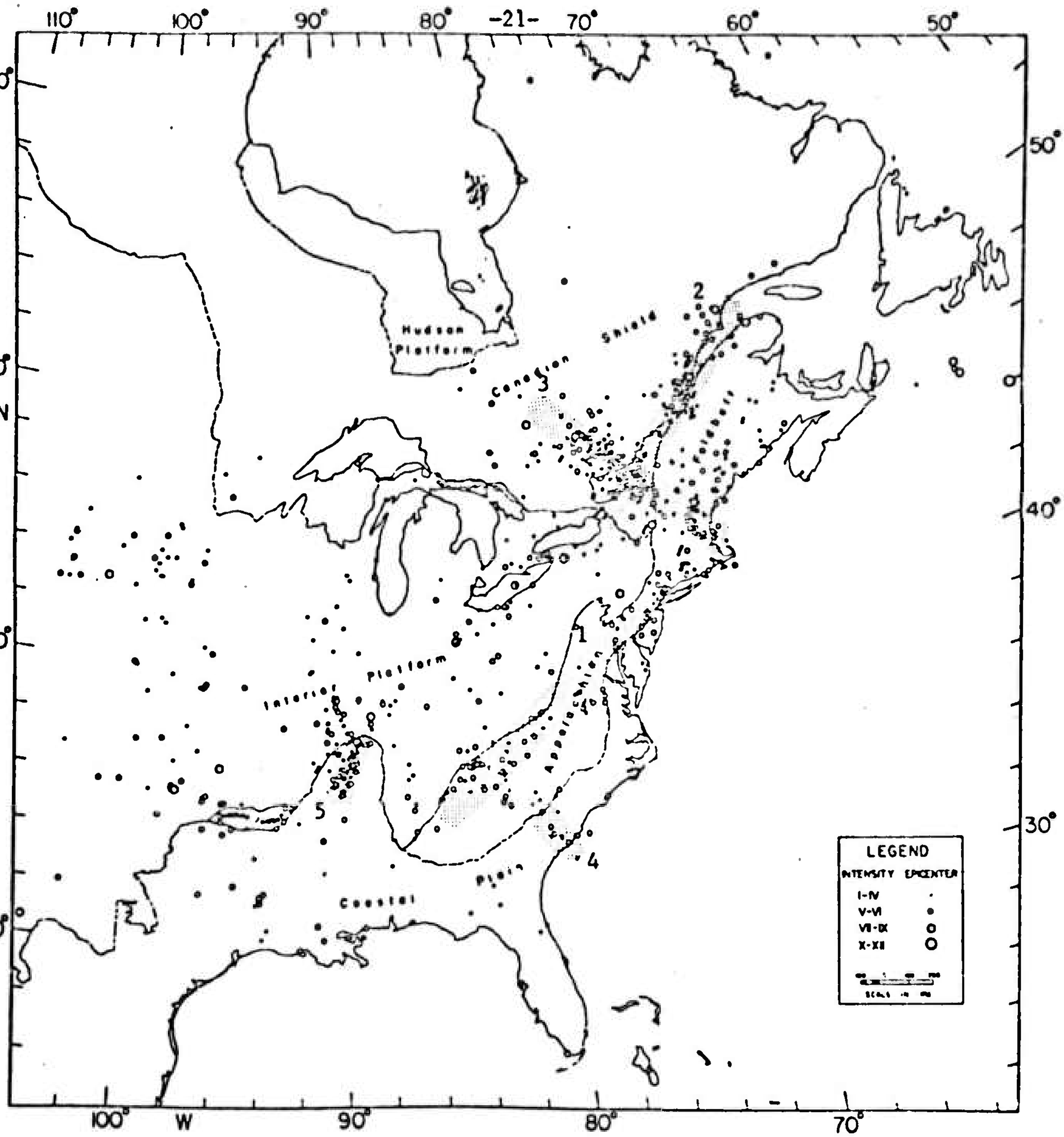
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Recent Vertical Crustal Movements in the Eastern United States as Determined by Precise Leveling

Results of releveling in the eastern United States obtained from the National Geodetic Survey have been analyzed in order to define contemporary movements of the earth's crust and determine whether or not such movements are related to the intra-plate seismicity of this region. It is found that the differing physiographic regions can be distinguished on the basis of releveling-determined movements and that these differences may be reflected in the seismicity of these areas.

Figure 2 is an index map of the routes of leveling for which continuous relative velocity profiles have been derived, superimposed on the Tectonic Map of North America. The data for these lines are plotted in Figures 3a,b,c,d,e,f. The left ordinate of these plots represents the vertical velocity of apparent crustal movement relative to some reference velocity, here arbitrarily chosen for plotting convenience. It is the shape of the plot rather than the absolute velocities involved which is of consequence here. The right ordinate represents the absolute elevation with respect to present-day sea level at the point of velocity measurement. The abcissa represents distance along the leveling route from the first bench mark. The profiles in Figures 3a,b,and e (ref. Figure 2) which traverse the Coastal Plain province indicate a consistent oceanward tilt. The magnitude of this secular tilting (up to $5x10^{-8}yr^{-1}$) is 2 to 3 orders of magnitude larger than rates derived from sedimentation studies (Menard, 1961). Extrapolation of these rates over the past million years would imply the existence of an Appalachian Highlands region several kilometers above sea level. It seems clear therefore, that these movements must be oscillatory with some period less than about 100,000 years. Routes which have been leveled more than twice suggest that the period of these oscillations may be on the order of tens of years.

A comparison of the EW profiles in Figures 3a and b, which transversely cross the Appalachian Highlands, with the EW profile in Figure 3c, which is entirely within the Coastal Plain, demonstrates clearly the relative uplift of the Appalachian Highlands with respect to its bounding provinces. As mentioned previously, these rates are several orders of magnitude larger than the average post-Jurassic rates. The pattern of vertical movement across the Appalachian Highlands defined in Figures 3a,b, and e appears to be one of alternate maxima and minima in the relative velocity (note vertical arrows). The similarity of movements in each profile invites correlation of these trends from profile to profile, thus implying a sequence of linear crests and troughs of relative velocity subparallel to the Appalachian orogenic trend. Such a pattern tends to parallel the Appalachian drainage divide and implies a present day tectonic system operating independently of the structural grain of the Appalachian orogenic trend (Figure 4). Such an interpretation is not unique, however, in that one may postulate an east-west shift in correlation of peaks to obtain the pattern shown in Figure 5, where relative velocity troughs are denoted by the short dotted lines and peaks by the solid lines. Such a correlation reflects the structural trend of the Appalachians. Also shown on Figure 5 is the seismicity of the eastern United States (unpublished map, Isacks and Oliver, by permission). A strong correlation of vertical movements and seismicity is suggested, especially along the Appalachian trend and in eastern Ohio. The lack of seismicity between the regions may reflect the complex smaller magnitude movements indicated by leveling in these areas.

The interior lowlands region appears to be dominated in the north by an areally large eastward tilt of about $1\text{-}4 \times 10^{-8} yr^{-1}$. To the south this pattern loses much of its consistency, indicating a more complex tectonic regime. The New Madrid seismic zone may be a correlated feature of such complexity.

Examination of the possible sources of error inherent in leveling has failed to reveal an error of sufficient magnitude to account for all of the apparent movements. The inconsistencies found between leveling results and water level data may reflect non-tectonic influences of water levels that have not been accounted for. It thus appears that leveling can provide a significant tool with which to develop a contemporary tectonic model for the eastern United States as well as other normally aseismic areas.

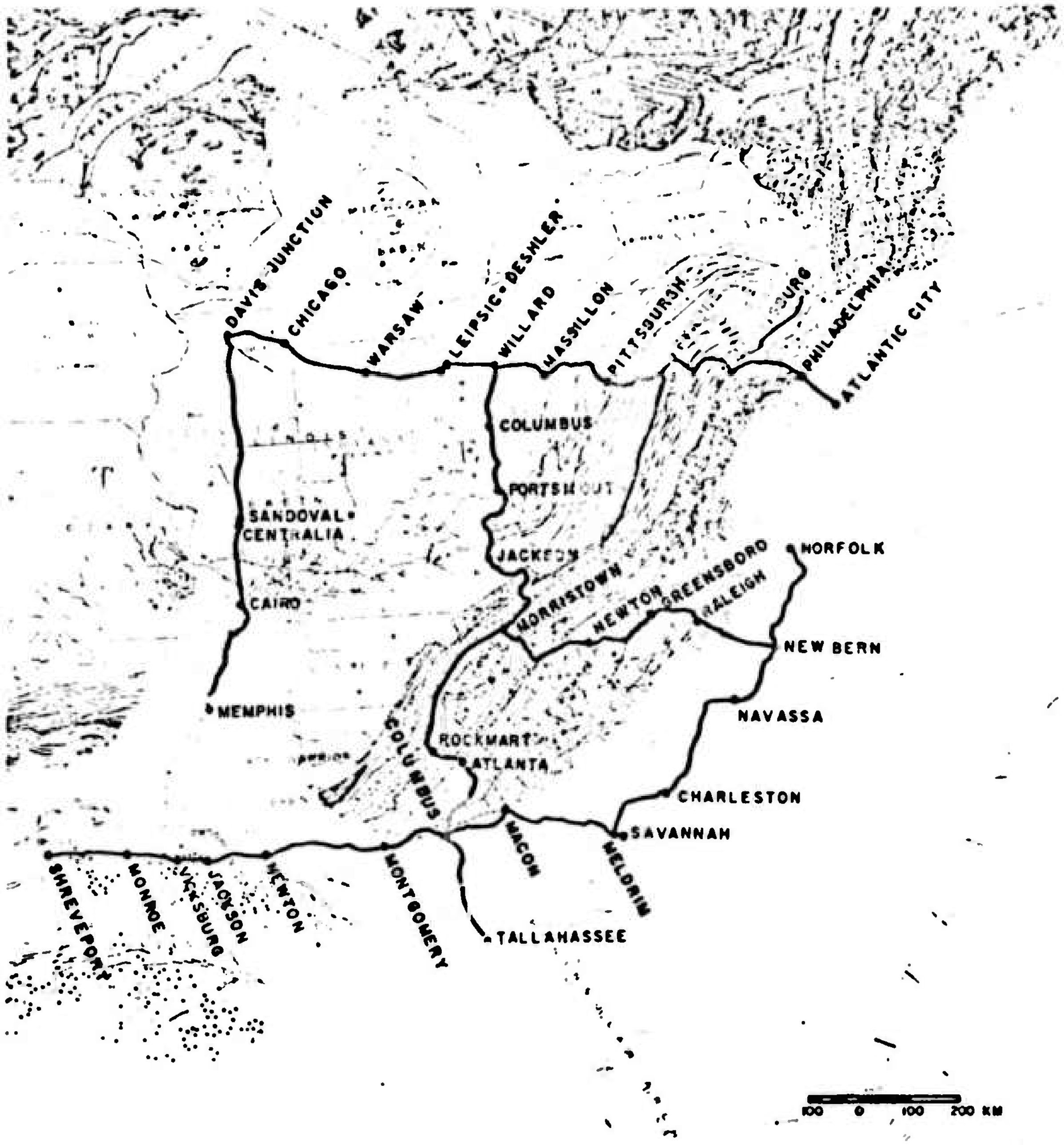

Figure 2. Index map of leveling routes for which data is plotted in Figures 3a-f. Base map is the Tectonic Map of North America.

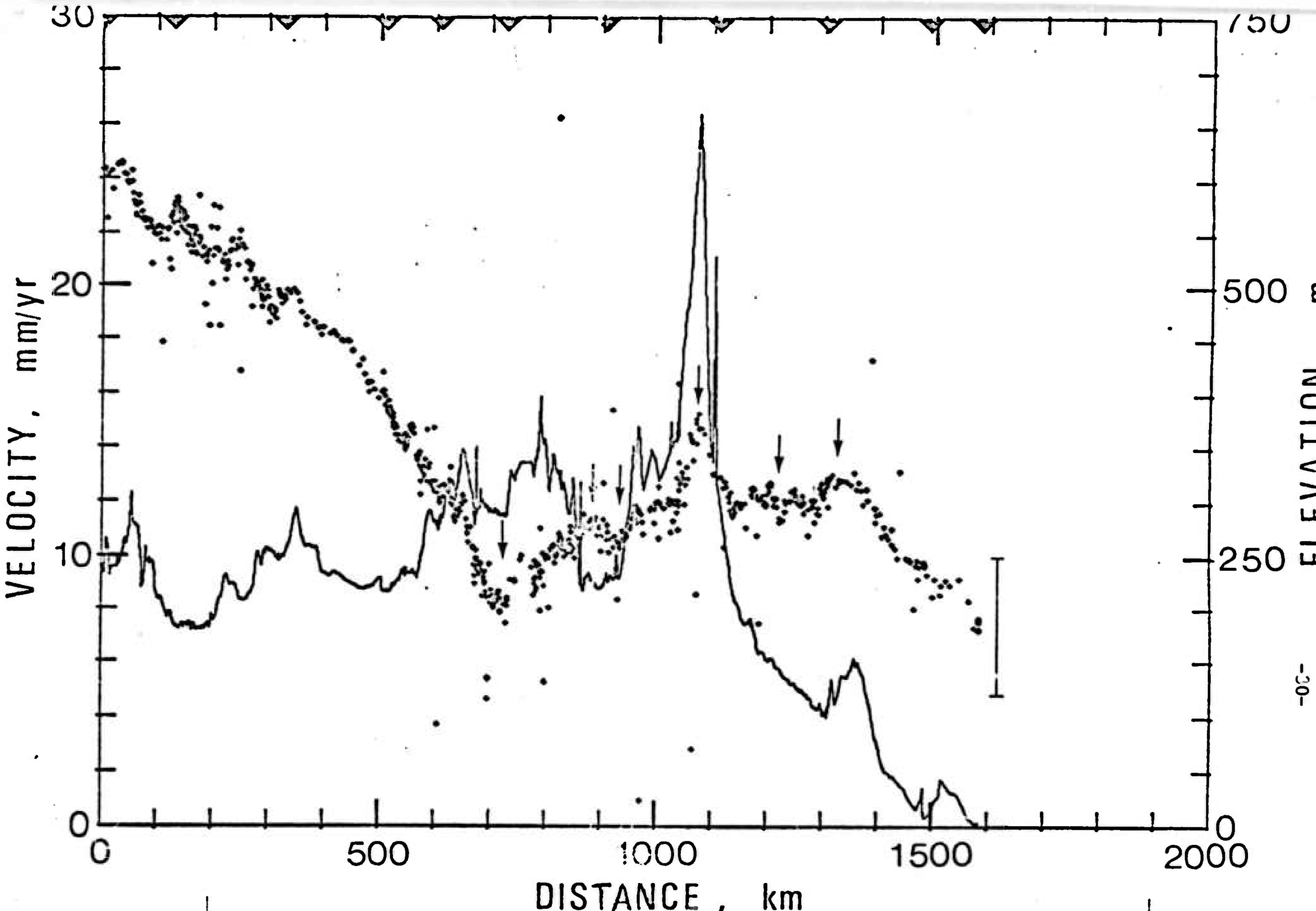

Figure 3. Profiles of relative velocity. Error bars give estimates of the error of the velocity of the end point relative to the initial point. Relative errors for values in between are correspondingly smaller. Vertical arrows represent velocity peaks and troughs used for correlation purposes. Solid triangles mark the positions of the cities indicated in Figure 2. Solid line represents absolute elevations along leveling route.

a) Davis Junction, Illinois to Atlantic City, New Jersey.

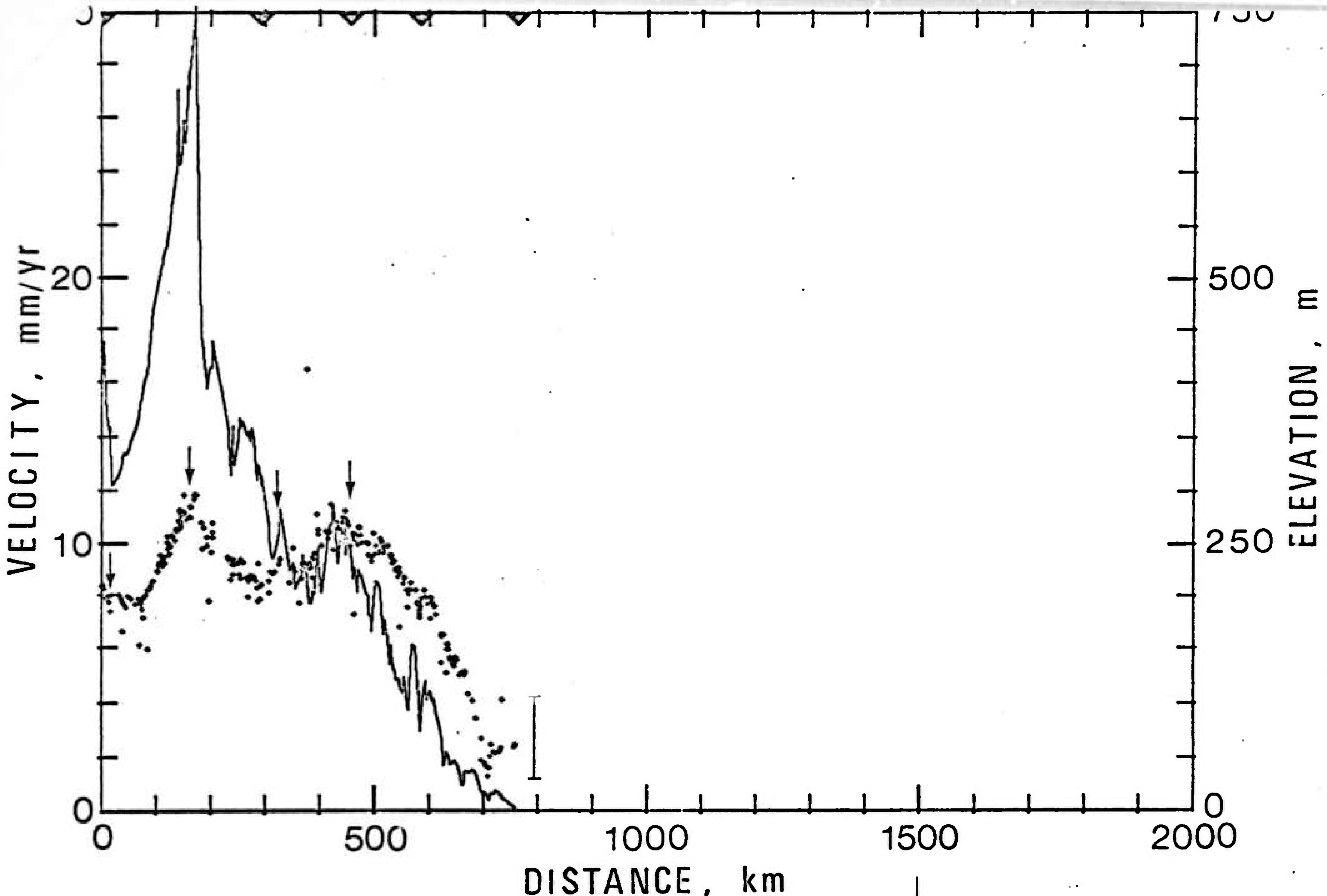

Figure 3b. Morristown, Tennessee to New Bern, North Carolina

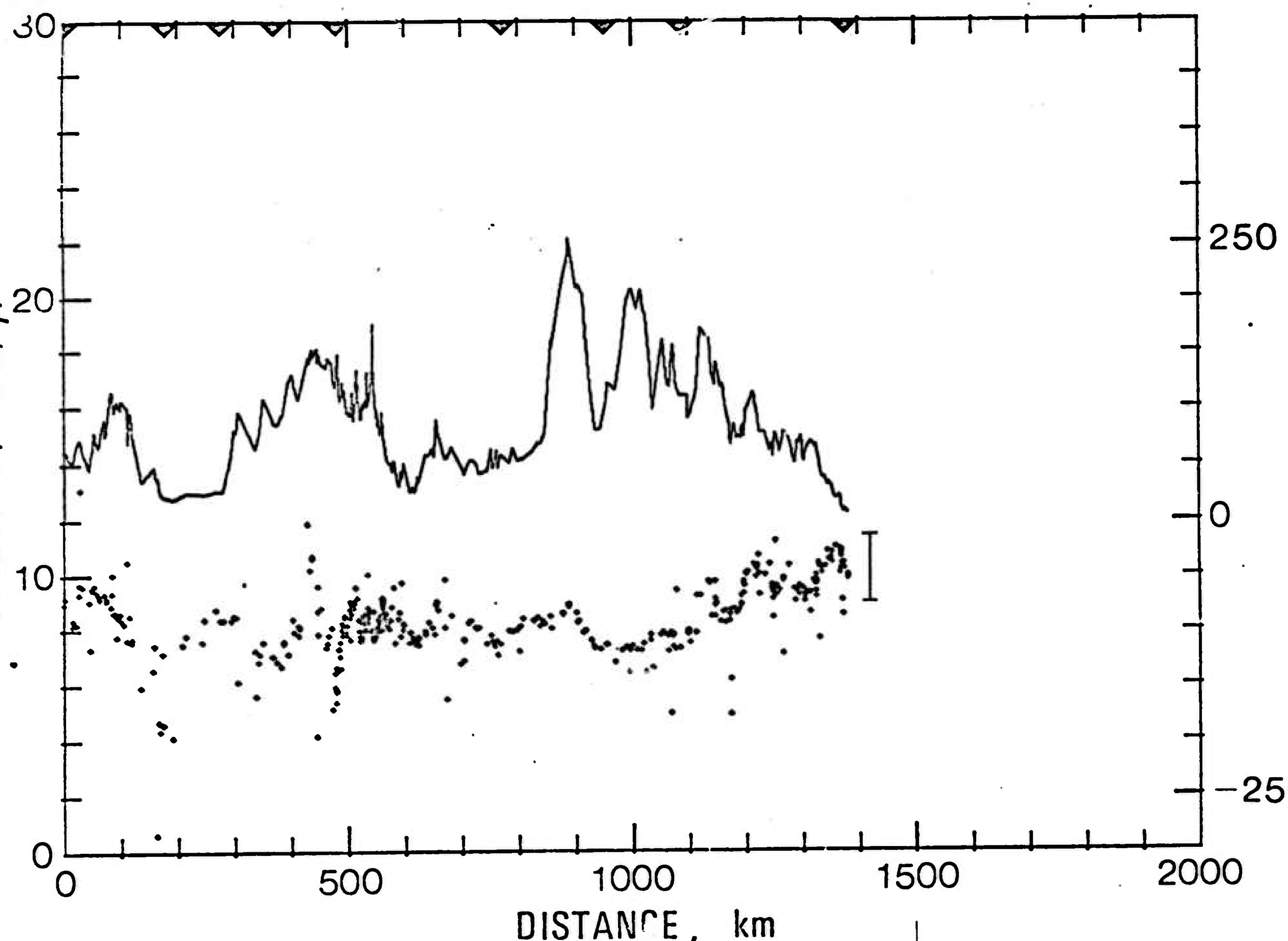

Figure 3c. Shreveport, Louisiana to Savannah, Georgia.

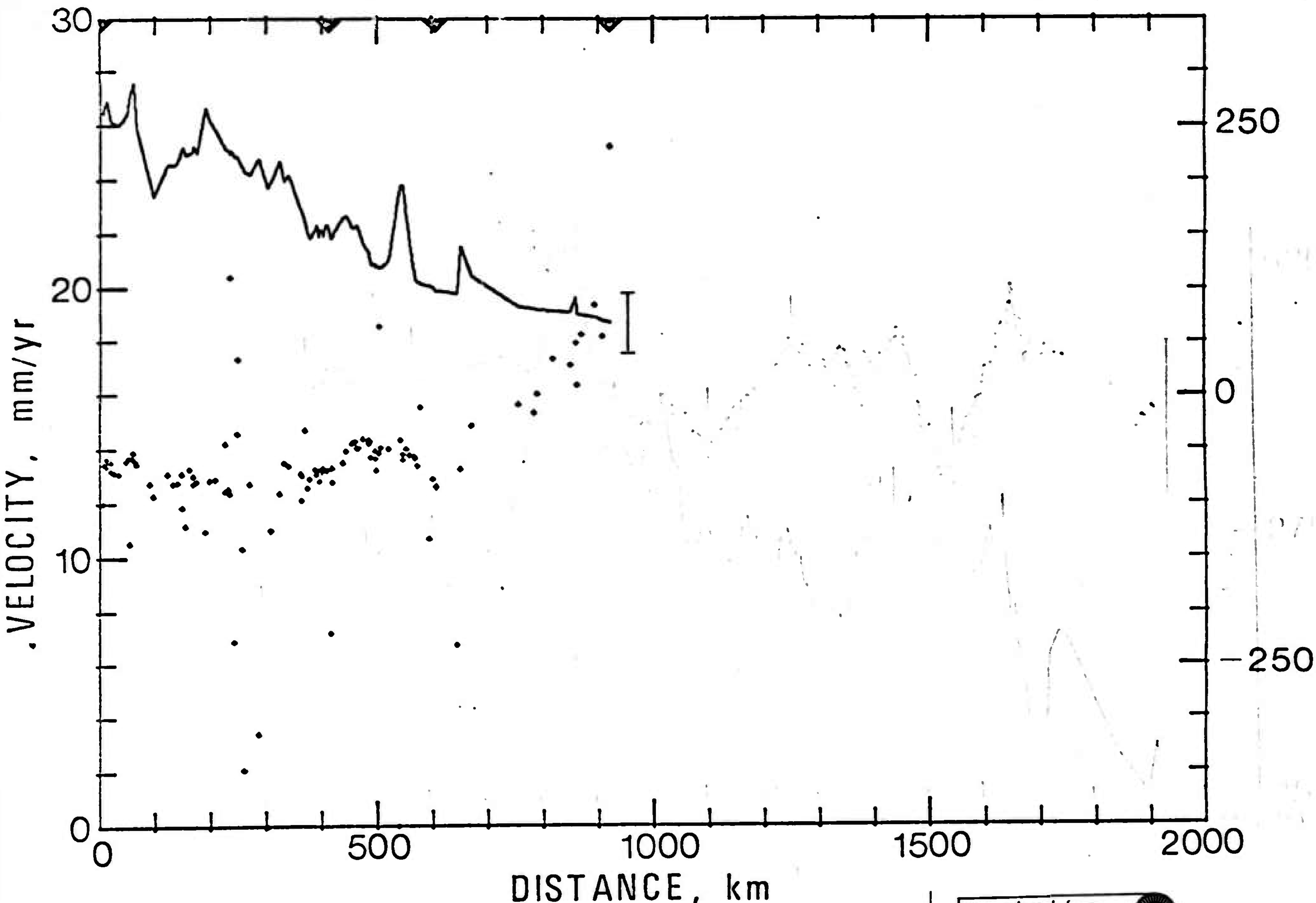

Figure 3d. Davis Junction, Illinois to north of Memphis, Tennessee.

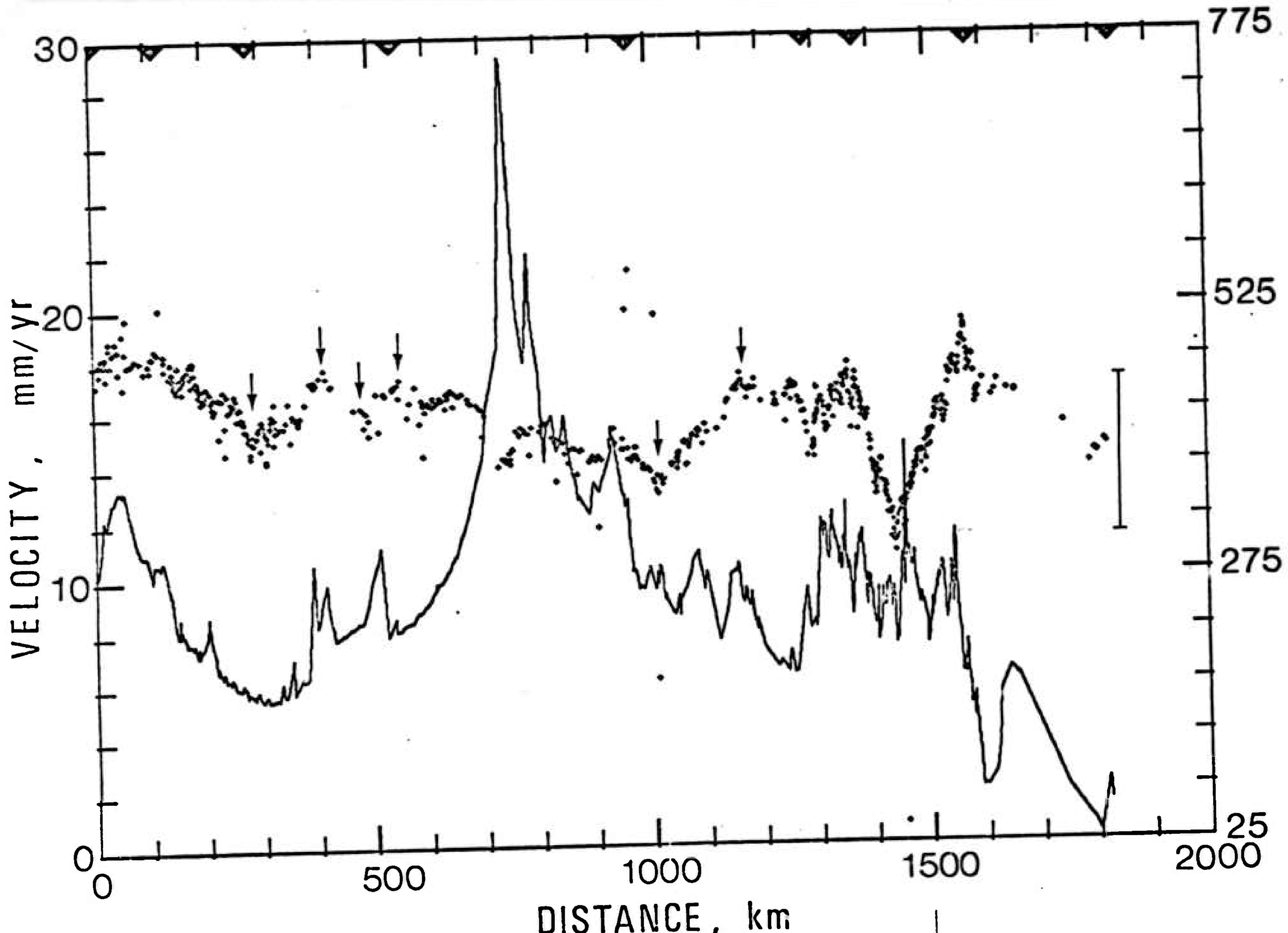

Figure 3e. Willard, Ohio to north of Tallahassee, Florida.

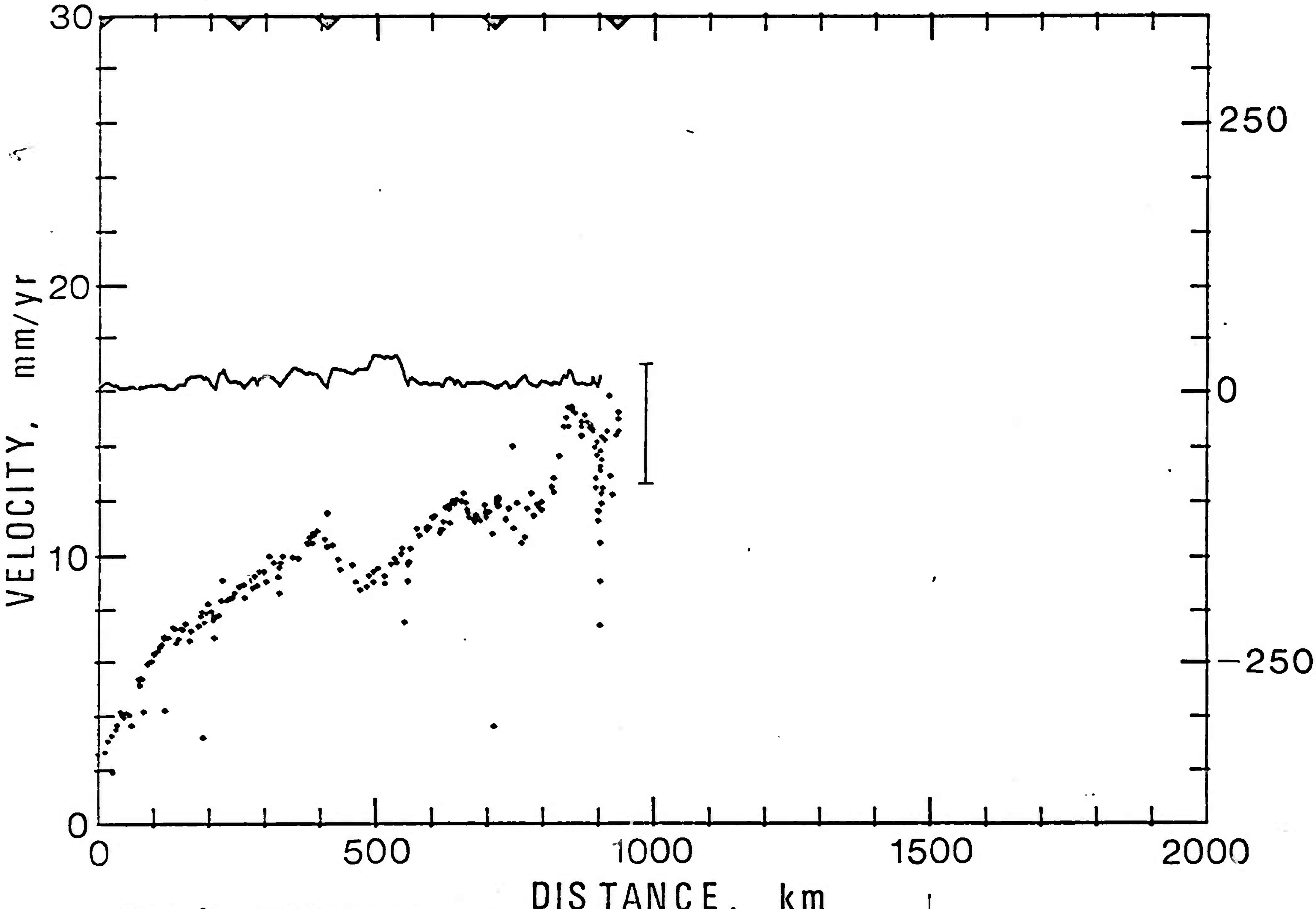

Figure 3f. Norfolk, Virginia to Savannah Beach, Georgia.

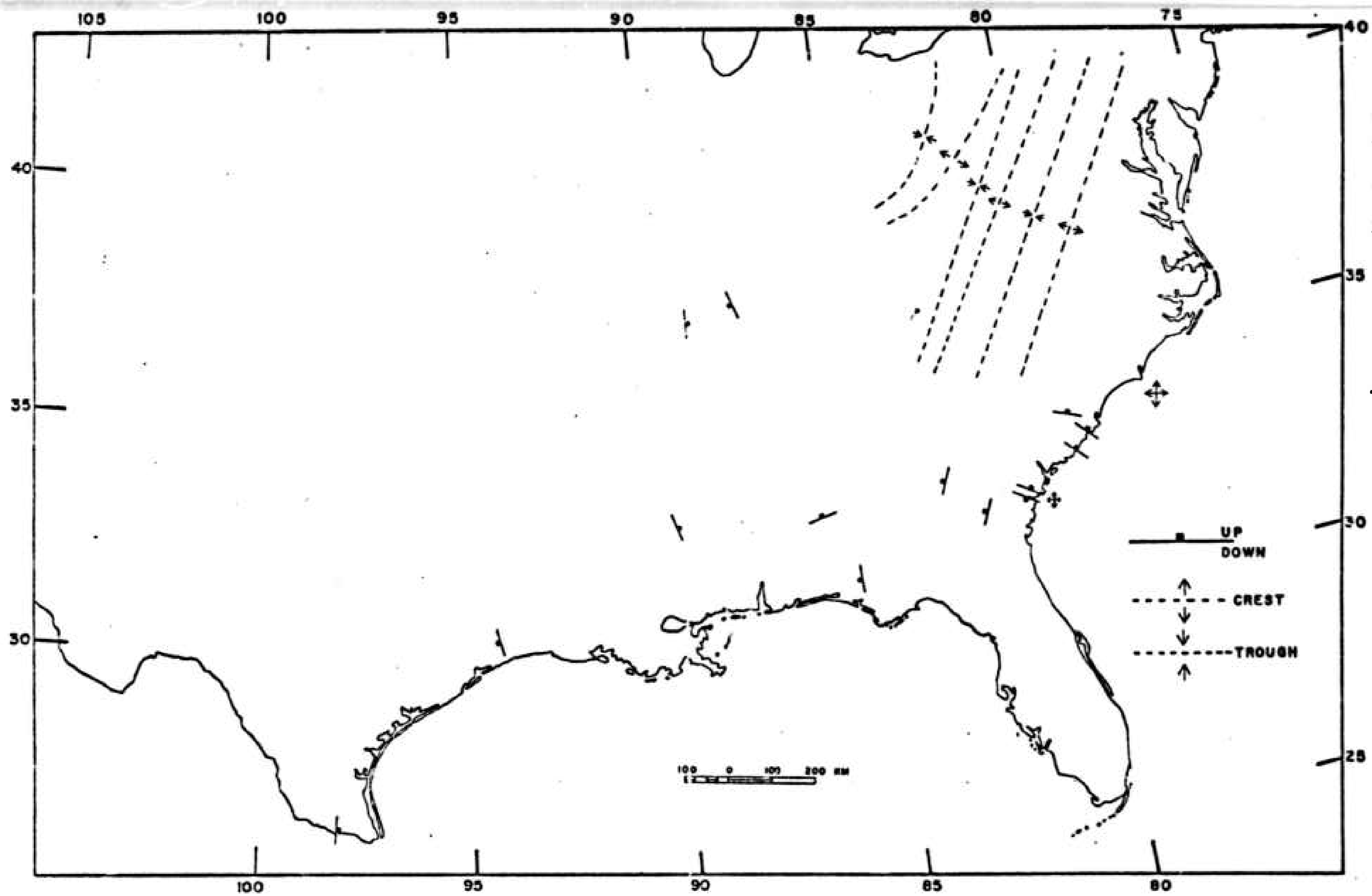

Figure 4 Leveling defined features in eastern North America. Straight solid lines with squares represent offsets in leveling. Crossed arrows represent domal features. Dotted lines represent crests and troughs in relative velocities.

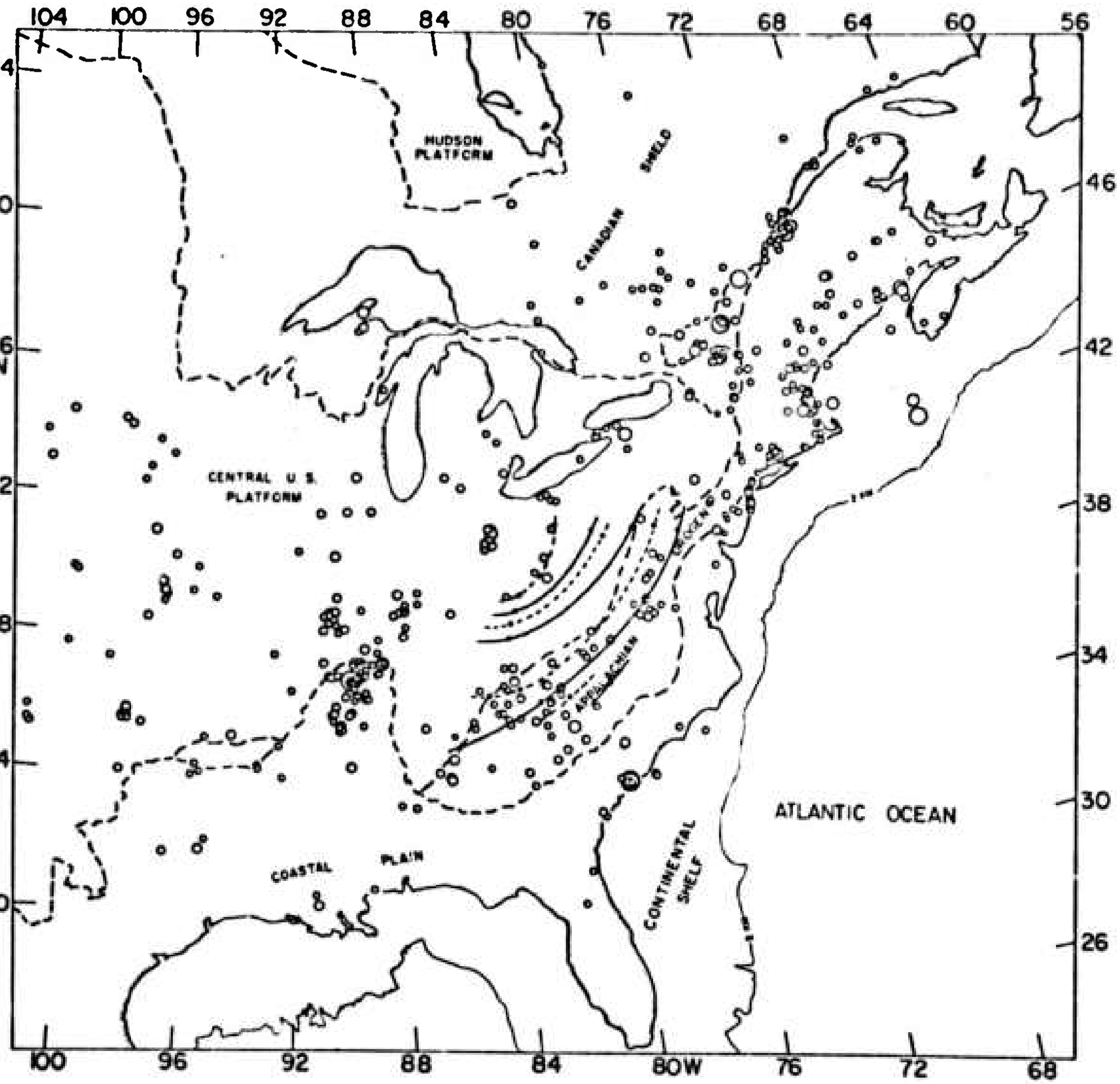

Figure 5. Velocity patterns defined by leveling superimposed upon seismicity map for eastern United States. Solid lines represent crests, dotted lines represent troughs.

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